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VLBI in the Deep Space Network: Challenges and Prospects

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Abstract

The purpose of this paper is to highlight the current status and prospects for VLBI in the NASA DSN. Although the prime purpose of the DSN is to support spacecraft operations and space research in deep space, this unique facility is also used on a noninterference basis with flight projects to support ground-based science experiments. The DSN VLBI capabilities are an integral part of a number of space- and ground-based projects. They include support of experiments at major radio astronomy VLBI networks (e.g., VLBA, EVN, APT), space VLBI co-observing, as well as VLBI geodesy and astrometry programs. The paper will describe for the potential DSN VLBI users 1) DSN VLBI objectives, 2) the current organizational structure and 3) current and projected capabilities.

1. Introduction

The NASA Deep Space Network (DSN) is a unique set of facilities distributed worldwide with the prime goal of supporting spacecraft operations and research in deep space. To conduct tracking of spacecraft in deep space, the DSN uses state-of-the art technology and instrumentation which is sometimes similar and often identical to radio astronomy instrumentation. From the time of the DSN's creation in the early 1960s, the radio astronomy community recognized great value in this facility for radio astronomy. Since then, the unique features of the DSN have been regularly used to do ground-based radio astronomy of which Very Long Baseline Interferometry (VLBI) is a very large part.

The DSN supports scientific experiments on a noninterference basis with the flight operations of space projects. This scientific support is carried out in three scientific disciplines: Radio Astronomy (radiometry, spectroscopy, polarization, VLBI), Radio Science (utilizing signals of interplanetary spacecraft to obtain information on the solar system's interplanetary environment, planetary atmospheres and fundamental physics), and Radar Astronomy (utilizing 0.5 megawatt transmitters).

2. DSN VLBI Objectives

The prime function of the VLBI capabilities at the DSN is to provide direct or indirect support to flight projects. This support can include: 1) VLBI navigation (including the maintenance of the navigation reference sources catalog), 2) Platform Parameters (station locations, calibration of Earth rotation and pole motion), 3) ground-based observing in support of space astronomy missions (e.g., Space VLBI, Gravity Probe-B). The infrastructure developed for these prime VLBI capabilities is also utilized to develop and support other DSN capabilities as, for example, antenna arraying and space VLBI telemetry acquisition and tracking (SVLBI spacecraft phase/clock synchronization and precision navigation).

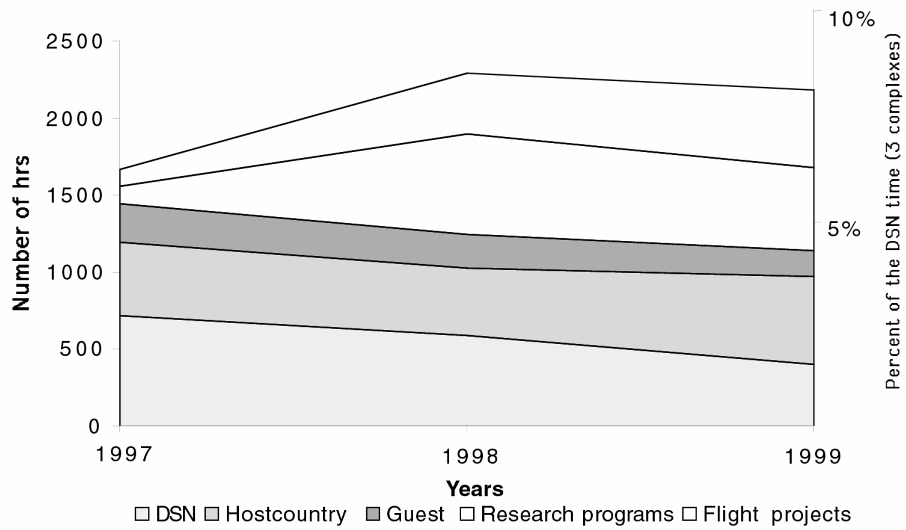

Figure 1. DSN time utilization for VLBI programs

Additionally, the DSN provides support for VLBI radio astronomy, geodesy and astrometry programs by 1) participating in operations of the major radio astronomy VLBI networks (e.g., Very Long Baseline Array, European VLBI Network, Asian Pacific Telescope), 2) providing an opportunity for "host country" radio astronomers to conduct their research at the Madrid (Spain) and Canberra (Australia) DSN complexes, and 3) carrying out various JPL/NASA research programs using DSN antennas.

The objectives of the DSN's participation in such research activities are 1) to realize and exploit the scientific and technical potentials of the DSN for enhancement of VLBI radio astronomy, geodesy, and astrometry sciences, and 2) to develop new DSN capabilities for support of scientific observations with ever-evolving VLBI techniques. Support of these activities requires developing and maintaining capabilities that are in addition to those required for deep space communication.

3. DSN VLBI Programs and Customers

DSN antennas have been used for VLBI since the inception of VLBI in the late 1960s. Radio astronomers were using them for pioneering VLBI experiments taking advantage of their superb sensitivity and longest baselines. A number of outstanding results in the fields of astrophysics, astrometry, and geodesy were obtained in VLBI experiments with DSN antennas.

A number of VLBI programs are currently conducted at the DSN:

1. Two VLBI radio astronomy programs are currently conducted at the DSN in support of flight missions: 1) VSOP (space VLBI co-observing at 70 m telescopes) and 2) Gravity Probe-B (monitoring of the proper motion of reference radio stars).

2. Two long-term ground-based VLBI programs: one geodesy (CORE) and one astrometry (VLBI detection of the extrasolar planets) are currently supported by the NASA Space Science Office.

3. Although the prime goal of NASA's Deep Space Network is to support space flight missions, in recognition of the value of large DSN radio telescopes for radio astronomy, NASA is allocating up to 3% of the DSN antennas time for ground-based radio astronomy research (guest observing programs). VLBI radio astronomers have been for a long time the major users of the DSN's radio astronomy guest observing time. The DSN antennas in Goldstone, CA, and Madrid, Spain, are participating in observational sessions of the EVN, VLBA, and Global VLBI.

4. The intergovernmental agreements between the US and Spain, and the US and Australia provide to radio astronomers in Spain and Australia so-called "host country" time at the DSN telescopes. This time accounts for about 1-2% of the DSN radio telescopes' time. The VLBI radio astronomy experiments, including astrometry and geodesy experiments (e.g. European Geodetic VLBI program, astrometric catalog of Southern hemisphere radio sources to extend the ICRF), consume a major portion of "host country" time in Spain and Australia.

5. Additionally, the DSN/JPL maintains DSN internal VLBI programs to monitor the earth rotation parameters (Clock Sync) and astrometric catalog of the reference sources for spacecraft navigation, Catalog Maintenance and Enhancement (CAT M&E). The results of these measurements are provided to the IERS Central Bureau on a regular basis.

Figure 1 shows the DSN time utilization for VLBI experiments and programs.

4. DSN VLBI Hardware and Operations Status

The DSN facilities include three major installations around the world: Goldstone, California, Madrid (Robledo), Spain, and Canberra (Tidbinbilla), Australia. The extremely large baselines between the DSN antennas/complexes and its strategic locations permit very high angular resolutions (close to the maximally possible at the surface of the earth) to be realized in VLBI observations between the DSN antennas and with other radio telescopes and interferometric networks. Additionally, high sensitivity (large collecting area, state of the art LNAs) and the ability to do VLBI phase referencing (fast antenna re-pointing, antenna clusters) have made the DSN facilities very valuable astronomical resources to conduct state-of-the-art VLBI experiments. Table 1 provides the current status of the DSN equipment which is utilized for VLBI observations.

All receivers have ambient loads and noise generators to provide automated measurements of the system temperature. Additionally, a Dicke-type beam switch is available which provides the capability for K-band radiometric measurement with reduced sensitivity to atmospheric fluctuations. The MKIV recording terminals (with dual recorder transports at each station) include the control computer running the PC Field System (PCFS) which can be controlled locally as well as remotely and automatically. The system configuration also includes the power meters to monitor the IF input levels.

The Deep Space Network has evolved to support the operations of deep space missions. The security required to support these operations with high reliability creates significant differences in the operating environment for the DSN radio telescopes compared to regular radio telescopes. While the PCFS computer provides a high level of compatibility with other VLBI installations, it cannot function as a prime DSN station computer. Instead, two additional computers, the Equipment Activity Controller (EAC) and the Radio Astronomy Controller (RAC), are used to interface the PCFS computer with other DSN subsystems. In effect, the EAC and RAC make the rest of the DSN appear like a radio astronomy observatory to the PCFS while providing a high

Table 1. Current Status of DSN Equipment Used for VLBI

DSN Complex, Location	Antenna	Dia - meter (m)	Frequency Bands (GHz)	SEFD (Jy)	Polarization, Channels configuration	Frequency standard, Clock	VLBI recorders
Goldstone, CA, USA	DSS13	34	31.9-32.1, 40-50,	300, 900	LCP, RCP, S&X simult.	Hydrogen maser, GPS	MKIV
Goldstone, CA, USA	DSS14	70	1.6-1.73, 2.2-2.3, 7.9-8.7, 18-26	40, 15, 20, 55	LCP& RCP simult., S&X simult.	Hydrogen maser, GPS	MKIV
Goldstone, CA, USA	DSS15	34	2.2-2.3, 8.4-8.5,	165, 130	LCP, RCP, S&X simult.	Hydrogen maser, GPS	MKIV
Canberra, Australia	DSS43	70	1.6-1.73, 2.2-2.3, 7.9-8.7, 12-18, 18-26	40, 15, 20, 50, 55	LCP& RCP simult., S&X simult.	Hydrogen maser, GPS	MKIV, S2
Canberra, Australia	DSS45	34	2.2-2.3, 8.4-8.5,	165, 130	LCP, RCP, S&X simult.	Hydrogen maser, GPS	MKIV, S2
Madrid, Spain	DSS63	70	1.6-1.73, 2.2-2.3, 7.9-8.7, 18-26	40, 15, 20, 55	LCP& RCP simult., S&X simult.	Hydrogen maser, GPS	MKIV
Madrid, Spain	DSS65	34	2.2-2.3, 8.4-8.5,	165, 130	LCP, RCP, S&X simult.	Hydrogen maser, GPS	MKIV

degree of security to the DSN. Additionally, the DSN VLBI Schedule Processor (DVSP) provides a bridge between a user which submits its VLBI schedule file through the Internet and the secure networks internal to the DSN. The schedule (VEX format) is preprocessed at the DVSP to check its validity (including correctness of the scheduled DSN time, format, etc.).

The DSN VLBI capability includes also the XF type VLBI correlator (Block II) which is capable of processing the MKIV VLBI data. The correlator has four MKIV playbacks. It is used mainly to process the DSN/JPL internal VLBI programs data.

5. DSN VLBI Organization

The Plans and Commitments Office of JPL's Tracking and Mission Operations Directorate (TMOD) is the prime organization within the DSN which establishes and maintains the interface with the DSN VLBI external customers. Among its responsibilities are: 1) establishing appropriate technical and organizational interfaces with the projects and VLBI organizations, 2) managing the space VLBI co-observing operations and VLBI operations for radio astronomy and geodesy, 3) organizing a review of the proposals for guest observations at the DSN, 4) providing the requests for the allocation of the necessary DSN time, 5) providing the guest radio astronomers with the necessary expertise to successfully execute observations with the DSN radio telescopes.

The development and implementation of VLBI capabilities at the DSN is the responsibility of the DSN Engineering Office while operation and maintenance are under the purview of the DSN Operations Office, both within the TMOD. These offices respond to the requirements provided by the Plans and Commitments Office, allocate the budget for necessary developments, and manage implementation and maintenance of the VLBI equipment including the correlator.

The day-to-day VLBI operations are the responsibilities of the JPL/NASA contractor personnel. The Customer Service Representative (CSR) and Network Operations Engineer (NOPE) are the prime contact for users to monitor the status of the project and resolve inconsistencies in the schedule. The station radio astronomy engineer and "friend" of the DSN telescopes (in Madrid and Canberra) usually help with the setup of the experiment configuration, calibration and conduct the observations. (For contact information see http://deepspace.jpl.nasa.gov/dsnscience/)

6. Opportunities and Challenges

The space VLBI requirements have been the major driver for the upgrades and improvements of the VLBI DSN system in the last decade. They have initiated at the DSN the upgrade of the VLBI recorders to MKIV and the upgrade of the K-band receivers at the 70 m sub-network. A new VLBI user interface and operational system based on a PCFS and three other controllers (DVSP, EAC, RAC) provides simpler access to users to the VLBI DSN system and more reliable operations. Additionally, the 11 m antenna sub-network has been built through the extensive use of VLBI technology to collect high data rate spacecraft telemetry (up to 144 Mbit/s) and provide clock synchronization and high accuracy navigation in order to support the space VLBI missions operations.

It is likely that the space VLBI missions will be the most demanding customers for the DSN VLBI in the future. Particularly, future SVBI missions will need 1) ground telescope co-observing support (only one antenna in space; at least one other antenna required to have the interferometric fringes), 2) ground telescopes with large apertures (antenna in space rather small), 3) high-precision apertures able to operate at millimeter wavelengths, and 4) telescopes located around the world and especially located close to the spacecraft tracking stations to enable real-time correlation. These future SVLBI VLBI needs for co-observing are naturally fulfilled by the DSN capabilities.

The future space and ground-based VLBI technology driven by science tends to evolve to 1) higher frequencies (space VLBI 22, 43, 86 GHz, millimeter wavelength VLBI), 2) wideband (up to 1–8 Gbit/s) recording and processing, 3) precision calibration, and 4) highly reliable VLBI operations. These and other capabilities need to be implemented at the DSN to enable support for future space VLBI missions as well as to participate in the work of the major radio astronomy and geodesy VLBI networks.

The DSN already began the implementation of the S2 VLBI recording at the DSN complexes. In addition to the S2 recorder in CDSCC which is maintained by CSIRO, the DSN will install in the next two years S2 recorders at all three complexes and interface them with the operational DSN equipment. Also, the DSN is developing a software correlator which will eventually be installed at each complex and used for real-time fringe verification. Currently, the prototype of this correlator is used for the ground-based testing of the SVLBI project Radioastron space radio telescope. To provide support for the internal DSN VLBI projects, the DSN is implementing a new VLBI correlator successor to Block II. The correlator will be capable of processing the MKIV data and will have four playbacks.

The DSN is currently undergoing significant organizational changes which may influence the interfaces with the DSN VLBI science users. Two major paradigms are the themes of these changes: the service provider and full cost accounting. VLBI became one of the services (along with other science services: Radio astronomy, Planetary radar, Radio science) which the DSN provides customers. These may, for example, introduce certain difficulties in rapidly implementing the new capabilities. "Full cost accounting" will eventually assign a cost of the DSN operations to every project supported by the DSN. The algorithm and procedures are still evolving. The impact of the implementation of full cost accounting on the DSN science services is not clear yet.